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HFDB-02 *"2nd Racetrack"* production report

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Abstract:

HFDB-02, a Racetrack magnet using reacted and wound Nb_3Sn, was fabricated at Fermilab at the beginning of 2002 (Dec. 2001 – March 2002). Because of its purpose and characteristics (R&D for the react and wind technology) it wasn't fabricated using a detailed traveler. Fabrication procedures were prepared before each operation was performed and they were often updated tacking into account the experience that was being built. These procedures have been collected in this report. In the appendixes some more documents and some pictures taken during the fabrication have been added. After the first thermal cycle the end plates were removed and the pre-stress in both ends was increased. Appendix 7 contains the procedure used and some pictures. Appendixes 8 and 9 contain data about the partial autopsy performed after the 2nd thermal cycle and the inspection of cable leftovers.

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Cable preparation for heat treatment

The content of synthetic oil was increased according to the following procedure.
Mobil 1 formula 0W-30 was used because it has the lowest viscosity (53 cSt at 40 C and 10 cSt at 100 C) among Mobil 1 oils.

Cable preparation:
- cut two pieces of Nb3Sn cable (from spool: R1O-00811 *see Appendix1*),
- length: 60 m and 70 m,
- wind each cable on a metallic spool,

Oil “impregnation” (performed at the Material workshop):
- each cable should be ‘impregnated separately’ in a plastic bag (polyethylene 5 mil thick) with two ports (one for vacuum, one for oil inlet)
- de-gas the oil in a vacuum chamber (use about 2 liters of oil per bag),
- prepare the bag and set felt bleeder-breather to avoid closing the ports,
- keep cable under vacuum overnight,
- slowly input the oil in the bag,
- stop when the spools are completely filled by oil (no more difference between inner and outer pressure),
- wait a few hours for a uniform distribution of the oil in the bag,
- close vacuum pump (actually we had to close it a few minutes after impregnation start because it was pumping the oil),
- heat up the spool (100 C for 3 hours).

Cleaning:
- make the spool stand in vertical orientation above the tank in order to let the extra oil drip in the tank,
- remove the cables form the spools and clean them with wiping rolls and paper,
- clean the spools,
- dispose oil and papers.

Heat treatment

The cable for each coil was reacted on a single layer stainless steel spool inside a reaction retort. The spool had a diameter of 360 mm. The heat treatment used was the standard HT suggested by the wire manufacturer (Oxford Superconducting Technology) performed in Argon atmpsphere:
ramp at 25 C/h to the temperature of 210 C and hold for 100 h,
ramp at 25 C/h to the temperature of 340 C and hold for 48 h,
ramp at 25 C/h to the temperature of 650 C and hold for 180 h,
ramp down at less than 75 C/h.
After the heat treatment there was a gap (about 2 mm maximum) between the innermost turn and the spool (Figure 1B). The gap was partially removed by rotating the core of the spool in the direction opposite to the cable winding.

Cable insulation

The cable insulation consisted in two tapes (a 6.5 mil pre-impregnated fiberglass tape and a 3 mil Kapton tape) wound together with the coil in order to form a continuous spacer between each couple of turns. See the Technical Division note TD-02-008 for more details.

Spot heaters

Four spot heaters were produced and measured at room temperature. Those installed in the magnet had resistance of 2.3 ohm at room temperature.

Fabrication

The magnet was fabricated according to the following procedure:

- Prepare insulation:
  - pre-preg tape with low epoxy content + 3 mil Kapton,
  - select the best rolls of pre-preg tape:
    - reduce the width of the insulation to 0.6 inch (pre-preg and Kapton)
      - check thickness and length of the pre-preg rolls (use rolls with similar thickness),
    - check width and thickness of tapes cut by a vendor and select the best rolls
    - NOTE: four rolls cut by a vendor were selected.

- Mechanical structure preparation for winding:
  - install bottom plate on winding table,
  - check the tensioners,
  - apply the ground insulation
    - on the main plates: four layers of 5 mil adhesive Kapton
    - on the end parts: two layers of 5 mil adhesive Kapton
  - set bottom-coil inner parts,
    - before installation, make the hole for the outermost pin larger than the pin, in order to compensate for the different thermal contraction,
  - install the spot heater,

- transition box:
  - make a large hole in the box for the wires that will exit from the top of the box,
  - use HGQ inner cable for the connection,
  - pre-tin the cable where it will be bent,
  - bend it around the G10 cylinder,
  - set voltage tap for quench protection (use a 22 gage wire),
  - close the box,

- Dummy winding:
  - set the roller table (fix the legs!)
  - install the spool with the dummy cable on the 1st tensioner (clockwise),
  - install the spool with the cable insulation on the 2nd tensioner.
  - make splice using the new fixture (practice with it),
  - wind 15 turns without side pushers
    - wind the innermost part and put the end spacers (use the pushers at this point),
    - apply some tension to the tape: 30 lbs.

        - check coil dimensions,
        - set the end parts,
        - make splice with NbTi current leads,
        - put voltage taps (check technique to put voltage taps after winding!!!)
            - the tapes should have a "V"cut, do it during the winding,
        - fix the end of the insulating tapes,
            - fix the tapes to the lead end pusher (before the gap for the splice and also along the gap for the splice)
            - add a pre-preg tape on the outside of the last turn
    - check the splice:
        - it's OK; 5 mil soldering strip is enough if all cables are pre-tinned but 10 mil helps to fill the cables inside,

- Mold-release and further preparation:
    - check if G10 box fits the hole in the plate (+ clearance for mold release)
        - if it doesn't file it,
    - paint with mold-release all parts which need it
        - (Note: <u>also the sides of the G10 inserts and the sides of the end parts</u>),
    - make grooves in G10 end spacers for VTs,
    - enlarge the grooves for VTs' strain-relief loops,
    - remove the gap between the cable and the metallic spool (created by different thermal contraction during cooling down after the HT)
        - rotate the core of the spool in the direction opposite to the winding direction,

- 1^{st} coil winding:
    - install the spool with the cable on the 1^{st} tensioner,
    - install the spool with the insulation on the 2^{nd} tensioner,
        - fix the beginning of the tape: glue it before inserting the splice and the cable,
        - pre-wind the first turn of insulation on the G10 pieces and cut V-shaped gaps to be used for VTs,
    - splice with NbTi cable:
        - add copper shims as stabilizers (2.35 mm thick),
        - pre-tin all the cables,
        - splice fixture should be strongly tight, but not at the maximum,
        - use two stainless steel foils or shims in order to avoid to splice the cables where they should separate (outside of the fixture),
        - clean the soldering coming out during the splicing in order to avoid that the splice doesn't fit,
        - <u>add 3-mil Kapton strip on the bottom of the splice</u>,
        - check splice thickness and compare with the distance between G10 teeth,
        - thickness of splice parts in mm: NbSn cable 1.20, NbTi cable 1.30, shims 4.70, TOTAL 7.2 mm
    - set the splice, the Nb_3Sn cable start and the NbTi cable,
    - Insulation (7 mil thick pre-impregnated E-glass tape + 3 mil Kapton)
        - wind it together with the cable,
        - insulation should be on both sides of each cable,
    - start winding:
        - tension on the cable: 20 lbs.,
        - tension on the tape: 30 lbs,
        - Don't use the side pushers (use them only to install the end inserts),

        - number of turns: 28 (14+14 - check the cable thickness after reaction and compare with drawings),
        - DON'T GO BACK DURING WINDING !!!
    - end inserts:
        - use screws in order to keep end parts in place during winding
        - **add 3 mil Kapton strip on the inner side of the end spacer**
            - apply mold-release on the surface looking at the end spacer,
    - end parts:
        - **check the ground insulation on the end parts, it should be:**
            - 11 mil in contact with the coil,
            - nothing outside
    - end of winding:
        - the turn-to turn insulation should be fixed to the lead end part,
        - a 3 mil Kapton tape should be set on the outside of the last turn,
            - apply mold-release on the surface looking outside,
        - cut the Nb_3Sn cable
            - keep seven feet of Nb_3Sn cable between NbTi leads,
    - splice: use two NbTi cable with copper stabilizing strips,
        - two copper strips 0.5 mm thick and 8 inch long on each side,
        - set splice partially outside the plate for better cooling (one inch),
        - set the voltage tap (BLRS2),

- Instrumentation:
    - put VTs
        - put VTs only on the top of the large face of the cable (to avoid stress concentrations),
        - make strain-release loops, apply gray RTV,
    - Set HT-Cernox,
        - check their resistance (about 60 ohm + 30 ohm in the wires)
    - put tags for VTs and Cernox,
    - COMMENT: the channels in the G10 layer should be deeper, the channels in the end should be larger in order to accommodate all the wires,

- Quench heaters (see Appendix 5):
    - fabricate two quench heaters:
        - stainless steel strip (1 mil thick) glued on a 3 mil Kapton foil + 5 mil Kapton strips (with gaps for epoxy flow) glued on another 3 mil Kapton foil,
    - bottom quench heater: make holes for the three outermost VTs in both ends, which should go through the G10 plate,
        - make new holes because the end spacers installed in the bottom coil were supposed to be used for the top coil (they have different position of the notches),
    - <u>Add holes and cuts to help epoxy flow from the grooves in the G10 plate (at least in the ends where there aren't the heaters)</u>,

- Inter-layer plate:
    - file the edges,
    - mold release both faces,
        - COMMENT AFTERWORD: put mold release on the top surface only after the plate has been installed and all wires are in position (otherwise glue and gray-RTV don't stick to the plate),
    - install the G10 plate,

        - put some gray-RTV where the wires of the VTs go from the bottom coil trough the G10 plate (to give some flexibility to the wires in case the G10 plate will separate from the bottom coil)
    - set wires for VTs in the ends,
        - partially cover with gray RTV in order to give some flexibility,
        - set tags for VTs,
    - add one layer of 3 mil Kapton (to prevent large amount of epoxy to be close to the cables)
        - the Kapton should have mold-release on the bottom surface (the one facing the G10 layer), so that cracks in the epoxy will not propagate to the epoxy close to the coil,
        - make cuts, close to the position of the VTs in the ends, in order to pick the wires,
    - check all VTs and the resistance of the Cernox sensors after the installation of the plate

- preparation for 2nd coil winding:
    - paint with mold-release all parts which need it
        - (Note: <u>also the sides of the G10 inserts and end parts</u>),
    - make grooves in G10 end spacers for VTs,
    - enlarge the grooves for VTs' strain-relief loops,
    - remove the gap between the cable and the metallic spool (created by different thermal contraction during cooling down after the HT)
        - rotate the core of the spool in the direction opposite to the winding direction,

- 2nd coil winding:
    - use the remaining of the cable used for the first coil in order to set up the fixture for the splice and the roller-table,
    - spool set up as for the 1st coil winding
    - splice with NbTi cable:
        - same as 1st coil winding except:
        - <u>add 3-mil Kapton strip on the TOP of the splice</u>,
    - set the splice and the G10 parts
        - be very careful!!!
        - use allens to keep the splice in place before you install the G10 pieces,
    - Insulation (7 mil thick pre-impregnated E-glass tape + Kapton)
        - wind it together with the cable,
        - insulation should be on both sides of each cable,
        - <u>fix the beginning of the tape: glue it after the splice is made,</u>
        - <u>while you wind the first turn of insulation on the G10 pieces, cut V-shaped gaps in the tapes to be used for VTs,</u>
    - start winding:
        - tension on the cable: 20 lbs.,
        - tension on the tape: 30 lbs,
        - Don't use the side pushers (use them only before installing the end inserts),
        - number of turns: 28 (14+14 - check the cable thickness after reaction and compare with drawings),
        - DON'T GO BACK DURING WINDING !!!
    - end inserts:
        - use screws in order to keep end parts in place during winding
        - **<u>solder the VT on the outside of the inner block before installing the end parts,</u>**
            - fill the cavity with glass-tape
        - **<u>add 3 mil Kapton strip on the inner part of the end spacer</u>**
            - apply mold-release on the surface looking at the end spacer,
        - raise the wire for VT on the inside of the outer block, and set it in the groove inside the end insert,

- end parts:
  - **<u>check the ground insulation on the end parts, it should be:</u>**
    - 11 mil in contact with the coil,
    - nothing outside.
- end of winding:
  - the turn-to turn insulation should be fixed to the lead end part,
  - a 3 mil Kapton tape should be set on the outside of the last turn,
    - apply mold-release on the surface looking outside,
- splice to NbTi cable with copper stabilizing strips,
  - two copper strips 0.5 mm thick and 8 inch long on each side,
  - set splice partially outside the plate for better cooling (one inch),
  - thickness of parts in mm: Nb_3Sn cable 1.20, NbTi cables 2.60, shims 2, TOTAL 5.8 mm
  - measured splice thickness: 7.6 –7.8 mm

- after 2nd coil winding:
  - <u>fill holes in the end pushers with gray RTV (to avoid epoxy to fill them)</u>
    - apply mold-release on the sides of the holes before putting gray RTV
    - make a Kapton cylinder around each bolt and leave it in the hole
  - fill gaps in the coil at the tips of the end inserts,
    - use 4 layers of pre-preg tape with different lengths in order to have a tapered spacer
  - cut the cable,
    - keep 7 feet of Nb3Sn cable between NbTi cables,
  - measure resistance and inductance of the coil:
    - R = 221.8 mohm (R from lead + to CF = 110.7 mohm)
    - L = .329 mH @ 20 Hz (Q=0.18) - .287 mH @ 1 kHz (Q=4.67).

- Instrumentation:
  - put VTs
    - put VTs only on the top of the large face of the cable (to avoid stress concentrations),
    - <u>put VTs on the current leads</u>,
    - make strain-release loops, apply gray RTV,
  - Set HT-Cernox,
    - set one close to the splice with current leads,
  - check their resistance (about 60 ohm + 30 ohm in the wires)

- Quench heater:
  - <u>Add holes and cuts to help epoxy flow from the grooves in the ground insulation (at least in the ends where there aren't the heaters)</u>,
  - <u>install it,</u>
    - before installation apply mold-release
    - cut the Kapton foil coming out of the magnet and leave it only to insulate the stainless steel strips,
    - add adhesive Kapton on the top of the strips,
    - remove part of the bottom Kapton layer (3 mil + 5 mil strips) over the coil in the lead end where the cables are slightly above the winding plane,

- Mechanical structure assembly and preparation for impregnation:
  - <u>check splice region in both coils and set appropriate spacers and cloths (3 mm G10 + 4 strips of pre-preg tape or fiberglass tape where there are wires)</u>,
  - put the shims(6 mm on non-lead side, 3.5 mm on lead side),

- use spacers in order to make the side bars fleet and to avoid over squeezing the coil (3.1 mm on non-lead side, 3.4 mm on lead side),
- don't use Al bolts, use the old ss bolt (Al bolts will be used after impregnation),
- preparation for impregnation:
    - put shrink tape around all bunches of wires, paint with mold-release, add RTV at the beginning,
    - put shrink tape around the cables, paint with mold-release, add RTV at the beginning,
    - remove tie-rods, put mold-release and grease,
    - put mold-release, grease and the bolts in the holes for G10 box support,
    - put mold-release, gray RTV and the bolts in the holes for splice cooling (both on top and bottom),
    - mold-release, grease and RTV on all bolts.

- Impregnation:
    - use CTD101K: 15 gallons,
    - book IB2 in advance,
    - monitor temperature and epoxy flow!!!
        - use the temperature sensors in the oven (thermocouples) to monitor temperature during the impregnation (one should be attached to the magnet),
        - COMMENT: next time use more than one thermocouple
        - put a ruler in the tank that could be seen from outside in order to measure the level of epoxy and regulate the flow,
    - pre-heat the magnet before starting the vacuum (otherwise it may NOT go to the right temperature),
        - COMMENT: we didn't do it,
    - use Al spacers and Teflon to avoid big pieces of epoxy close to the magnet,
    - curing temperature should not approach melting temperature of soldering (183-188 C for 60/40 tin/lead)
    - see appendix A for impregnation procedure

- Cleaning and instrumentation:
    - instrument bolts and calibrate gauges,
    - define instrumentation and connector details (see HFDB-02 DAQ System Interface)
    - perform Hi-pot test (see results in Table 1)

+	-	**V (volt)**	**I (μA)**
Coil	Ground	800	0.02
Coil	QH – top right	600	0.02
Coil	QH – top left	600	0.03
Coil	QH – bottom right	600	0.04
Coil	QH – bottom left	600	0.03
QH – top right	Ground	600	0
QH – top left	Ground	600	0
QH – bottom right	Ground	600	0
QH – bottom left	Ground	600	0
QH – top right	QH – bottom right	600	0
QH – top left	QH – bottom left	600	0

Table 1: Hi-pot test performed after the cleaning and before the application of pre-stress

- Pre-stress:
  - Pre-cycle: Hand-tighten all bolts on the side pushers and end plates until all the bolts are snug. All torques were applied to the bolts using two standard torque wrenches calibrated in in-lbs (for the bolts on side pushers and end plate) and ft-lbs (for main plates)
  - Cycle 1: All 32 bolts on the side pusher were torqued to100 in-lbs starting with the outside bolts and moving towards the inside.
  - Cycle 2: All 8 end bolts on the end plate were torqued to 150 in-lbs (outside bolts to inside bolts)
  - Cycle 3: All 32 side plate bolts were torqued to 200 in-lbs (outside bolts first to inside bolts next)
  - Cycle 4: All 8 end bolts were torqued to 300 in-lbs (outside bolts first to inside bolts next)
  - Cycle 5: All 32 side bolts were torqued to 250 in-lbs (outside bolts first to inside bolts next)
  - Cycle 6 – Cycle 9: All main bolts were torqued to1200 in-lbs in the following steps – 360 in-lbs, 720 in-lbs, 960 in-lbs and 1200 in-lbs (outside bolts to inside bolts)
  - Bolt stresses were monitored during the entire torquing cycle using calibrated strain gages mounted on four of the main bolts, two of the side bolts and two of the end bolts. The bolt load and coil pre-stresses for Thermal Cycle I are summarized Table 1.

Bolts	Torque (in-lbs) per bolt	Average Load per bolt (lbs)	Total Load (lbs)	Stress per Coil (MPa)
Main	1200	4800	273600	2.4
Side	250	1600	51200	8.1
End	300	2000	16000	9.0

Table 2: Bolt loads and coil pre-stress summary for Thermal Cycle 1

- Preparation for delivery to IB1
  - make a hole in the circular top flange to avoid bending of Nb_3Sn leads,

NOTES AFTER FABRICATION

- During the instrumentation of the top coil, the turns in the outer block of the lead end moved upward (see Figure 16). The maximum displacement was in the outermost turn and was a bit less than 1 mm. The outermost turn was easily set back in its original position. The other turns could be set back in their position using a G10 plate and a clamp, but they sprang back when the G10 plate was removed. It was decided to reduce the thickness of the insulation between this part of the coil and the quench heater (Figure 17).
- The lead end plate was supposed to be removed in order to clean it from epoxy and apply the pre-stress on the lead ends. The leads go through this plate and red RTV was set all around them in order to prevent the epoxy from bonding the leads to the plate. After impregnation it was found that the leads were bonded to the lead end plate. In order to avoid the risk of damaging the leads, it was decided to let the plate in position for the first thermal cycle (figure 20). It would have been removed before the second thermal cycle, in case the quench performances showed a lack of pre-stress in the led end.

Instrumentation check before delivery:

- Hi-pot test (after pre-stress was applied):
    - Coil to ground: $I<0.02$ μA at 1000 V,
    - Coil to heaters: $I<0.02$ μA at 1000 V,
    - Heaters to ground: $I<0.01$ μA at 800 V,
    - Bottom heaters to top heaters: $I<0.01$ μA at 600 V.

- Voltage taps:
    - only one Vtap is dead: T28d2.

- Temperature sensors:
    - CX 20386 (close to the splice to NbTi leads) is lost,
    - CX 20384: one wire is open TE-02 (V-),
        - proposed solution: three wire measurement putting a jumper between TE-02 (V-) and TE-02 (I-),
    - the labels on CX 20383 and CX 20385 were lost during the impregnation, we tried to fix the problem but we are not sure about it,
        - note: these temperature sensors are close to the spot heaters, they could be used to identify the sensors.

- Strain gauges:
    - MainR4C (a compensator for the big bolts) is broken,

- Heaters:
    - All of them are OK.

Appendix 1: Cable data

CABLE No. **FNL R&W-R1O-00811**
MFG. 8/01/01 LBNL
OPERATOR: H.Higley, E. Palmerston

CABLE LOG SHEET
LBNL-SUPERCON-AFRD
SUPERCONDUCTING MAGNET MATERIALS
BLD 52

Objective:
1) Nb3Sn 41 strand cable Identical to LBNL Cable # R1I-00799 using Oxford strand

- STRAND INFORMATION -

MANUFACTURER :	Oxford		
BILLET #:	Ore-151 & Ore-152		
SPOOL #:	See Respool Map. "stmpR1O00811_Ore151_152.xls"		
COMPOSITION :	Nb3Sn		
STRAND Dia.. NOMINAL :	0.7 mm	INSP. DIA..:	0.7034mm avg.
Cu/SC RATIO NOMINAL :		INSP. RATIO :	
FILAMENT TWIST/LENGTH :		DIRECTION :	Right
SHARP BEND TEST :			
LENGTH PER SPOOL :	150m, without leaders or trailers.		

- CABLING SPECIFICATIONS -

TYPE or SPEC.:	FNAL R&W -R1				
No. of STRANDS:	41				
PITCH DIRECTION:	LEFT	PITCH LENGTH:	110		
PLANETARY RATIO:	-.57				
ROLLER ID #:	P29 & 30	WIDTH:	15.006 mm	ANGLE::	**0**
MANDREL ID #:	39B	WIDTH:	14.32 mm	THICKNESS::	.58 mm
LUBRICATION :	MOBIL-1, 5% + Naphtha as thinner, approximately 1.5 drop/ pitch.				
STRAND TENSION:	2.5kg. +/- .1	TURKS HEAD LOAD "SGM":			

- FINISHED CABLE -

	R1O-00811
FINISHED LENGTH:	141m
Avg. THICKNESS:	1.2230 mm
Avg. WIDTH:	15.0714 mm
Avg. ANGLE:	-0.028 deg.
RESIDUAL TWIST/Mtr.:	90 deg. under twist " good direction"
ETCH for FILAMENT DAMAGE:	No damage, see photo.

Notes: This cable looks very good. It has a very uniform surface finish and minimal residual twist.
This cable is slightly wider than cable # R1i-00799, probably due to the decreased Cu content in the Oxford strand. The same increase in width was not measured for the 60 strand cables #802 & 803 because the cable measuring machine was not used.

Impregnation procedure for 2nd Racetrack

14-Mar-01 Version 2

	Set	Read	
C	**F**	**F**	
60	**140**	…	temperature during pumping (42 hrs)
60	**140**	…	temperature during impregnation
125	**257**	…	temperature during curing

Epoxy component and total weight

	volume	58	l	*15.32*	*gallon*
	density	1.20	kg/l		
	weigth	69.6	kg		
	one part	0.363446	kg		
parts:					
100	part A	**36.34**	**Kg**	80.14	lb
90	part B	**32.71**	**Kg**	72.13	lb
1.5	part C	**0.55**	**Kg**	1.20	lb
	Total	**69.60**	**Kg**	153.47	lb

Mixing temperature: 140 F (60 C)

Degassing: 1hour 15 minutes (starts when temperature is above 40 C)

impregnation procedure:

magnet at 140 F, epoxy at 140 F (60 C)

oven pressure: 30 Hg micron (during all process)

- first filling to reach coils bottom (first black mark on the level indicator),
- slow filling: increase the level of 1 inch/hour (1 line every 15 minutes)

curing procedure:

20 hours at 257 F (125 C)

Appendix 3: data recorded during impregnation

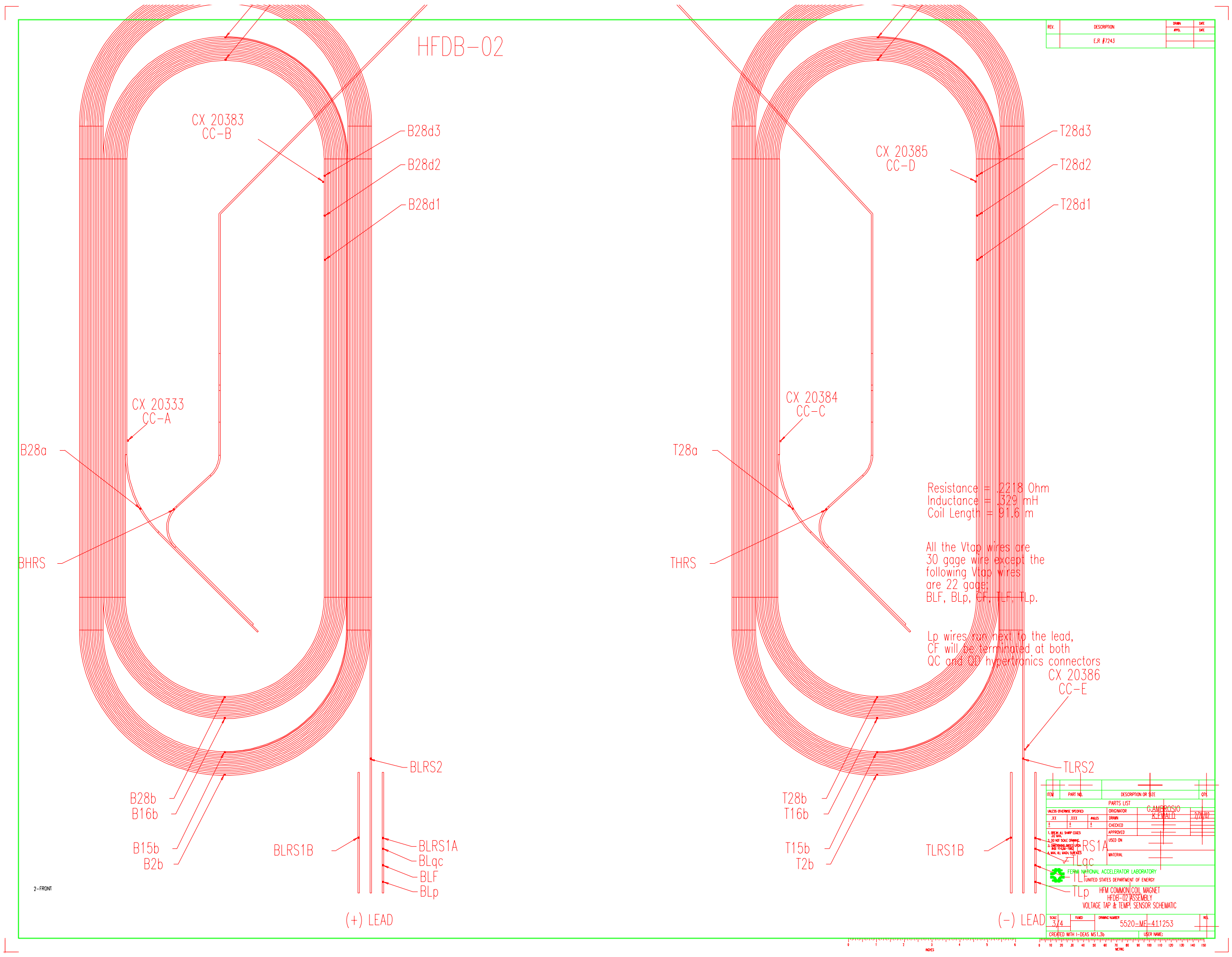
Impregnation of 2nd Racetrack

March 15, 2001

Technicians: Jesus and Cicil

time	temperatures Epoxy	Magnet (F)	Oven (F)	Th1 (F)	Th3 (F)	Th4 (F)	Epoxy level (in)	Action
								pump and heat started on th
8:20								start mixing
9:22		107	141					
9:25								oven set at 170
9:35	40 C							start degassing
10:40		109.1	169	141	156.3	151.3		
10:54		108.6	167	140.3	154.4	150.1		
10:50								stop degassing
11:08	58 C							START IMPREGNATION
11:16		109.7	166	140.5	153.9	150		
11:30		109.7	171	14.2	157.3	152.8		
11:35							1/4	
11:50							1	STOP impregnation
12:07								open again, very low flow
12:08		110.8	170	143.3	157.8	153.4		
12:40							1+3/4	
12:49		111.4	171	143.9	158.3	154.3		
13:45							2+1/4	
13:50		113	171	145	159	154.9		
14:00							2+1/2	
14:40							2+3/4	
14:45		113.9	171	145.7	159.5	155.4		
15:37		114.8	171	146.5	159.5	155.5	3+1/2	
16:00							3/4 above leads - flow increased	
16:15							1 above leads - STOP IMPREGNATI(	
16:20		116.7	171	146.5	159.7	155.1		
								epoxy left: 7.5 gallons
17:07		118.4	171	146.5	161.2	158.7		STOP VACUUM

Appendix 4: voltage tap locations



HFDB-02 "2nd Racetrack"

Voltage tap list and position

	Δl	Total	Dead/Alive	Note
BLp	0	0		
BLF	0	0		
BLqc	0	0		
BLRS1A	0	0		
(BLRS1B)	0	0		same location of BLRS1A on the second NbTi cable
BLRS2	200	200		
B1c	858	1058		
B2b	986	2044		
B14c	21215	23259		
B15b	837	24096		
B15c	796	24892		
B16b	755	25647		
B28b	18720	44367		
B28d1	325	44692		
B28d2	90	44782		
B28d3	90	44872		
B28c	126	44998		
B28a	499	45497		
BHRS	70	45567		
CF	225	45792		
THRS	225	46017		
T28a	70	46087		
T28c	499	46586		
B28d3	126	46712		
B28d2	90	46802		
B28d1	90	46892		
T28b	325	47217		
T16b	18720	65937		
T15c	755	66692		
T15b	796	67488		
T14c	837	68325		
T2b	21215	89540		
T1c	986	90526		
TLRS2	858	91384		
TLRS1A	200	91584		
(TLRS1B)	0	91584		same location of TLRS1A on the second NbTi cable
TLqc	0	91584		
TLF	0	91584		
TLp	0	91584		

Appendix 5: Quench heater

Racetrack 2

all heaters in series

magnet length	**0.8**	m
N. of Strips per Heater	4	
Strips in parallel	1	
N. of Heater in parallel	**1**	
N. of Heater in series	2	

Heater strip:	at 4 K			at 296 K	at 4 K
Strip width	1.0E-02	m		1.0E-02	1.0E-02
Strip thick	2.5E-05	m		2.5E-05	2.5E-05
rho aisi304	4.9E-07	ohm*m		7.2E-07	**4.9E-07**
rho aisi316	5.3E-07	ohm*m		7.7E-07	5.3E-07
A strip	2.5E-07	m2		2.5E-07	2.5E-07
R/length	1.96	ohm/m	(without Cu)	2.88	1.96
Cu cladding		**0 :1**			
Cu length	0.0E+00	m		0.0E+00	0.0E+00
SS length	1.2E-01	m	100%	1.2E-01	1.2E-01
SS length/strip	0.8	m	145%	1.2	1.2
R 1 strips	1.6	ohm		3.3	**2.274**
Tot heater R	6.3	ohm		13.36	9.1
Rwires	0.3	ohm		0.4	0.8
Rtot	**12.8**	**ohm**		**27.1**	**19.0**

SSC Capacitor Bank:		
C tot	1.44E-02	F
U tot	400	V
Vmax(V)	450	89%
E tot	1.2E+03	J
Po	8.4E+03	W
Po-Pleads	8.1E+03	W

P/A	**8.7**	W/cm2
decay time	**0.273**	s
Io	**21**	A
gen=Po/vol	3.6E+09	W/m3

ansys	
gen (W/m3)	T (K)
5.5E+10	10.4
2.8E+10	9.8
1.0E+10	9.5

Cable dimensions:								
ins	1.00E-04	m	drheated	1.40E-03	m	E/S	1.2E+04	J/m2
drcab	0.00144	m	ins	5E-04	m	**E/V**	4.4E+06	J/m3
dhcab	0.01516	m	DH	2E+05	J/m3	**E/V w ins**	3.3E+06	J/m3
strand	7.00E-04		DH	5E+05	J/m3	**diff**	177%	
						diff	147%	

Appendix 6: Pictures

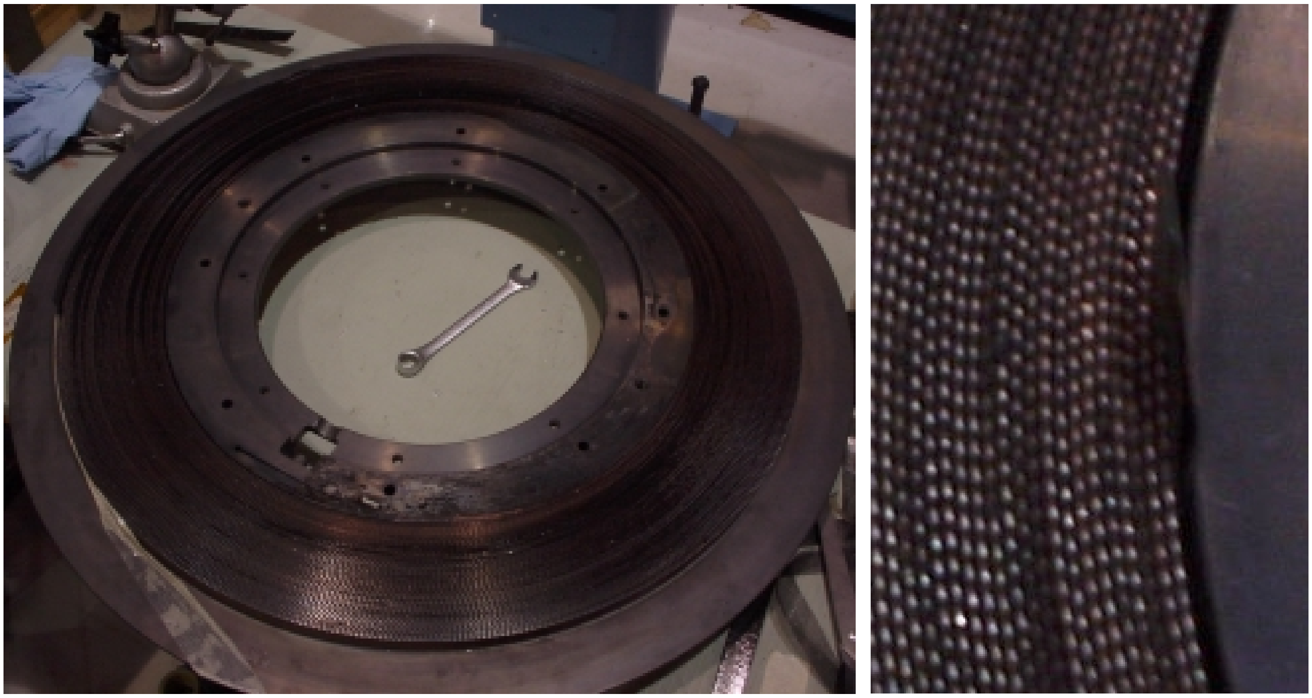


Figure 1: reaction spool with reacted cable. On the right detail of the gap between the first turn and the spool

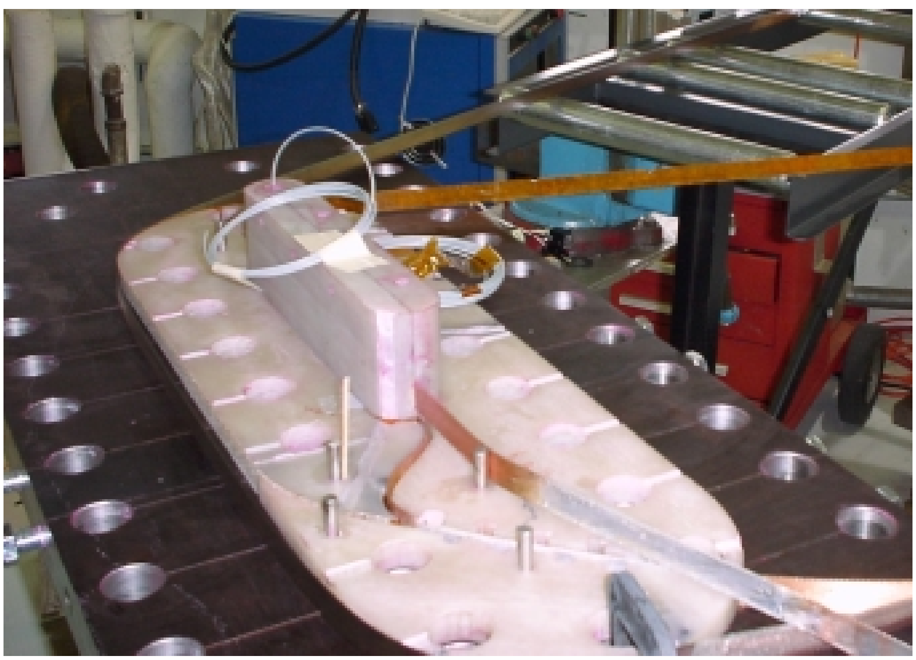


Figure 2: preparation for splice and winding of the first coil

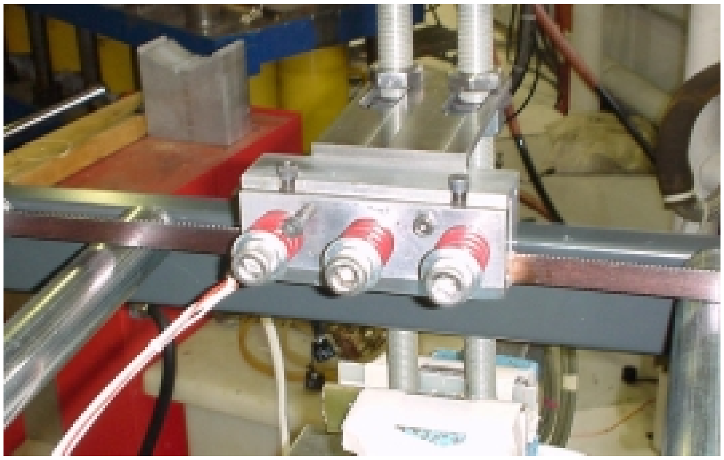


Figure 3: pre-tinning of the Nb_3Sn cable

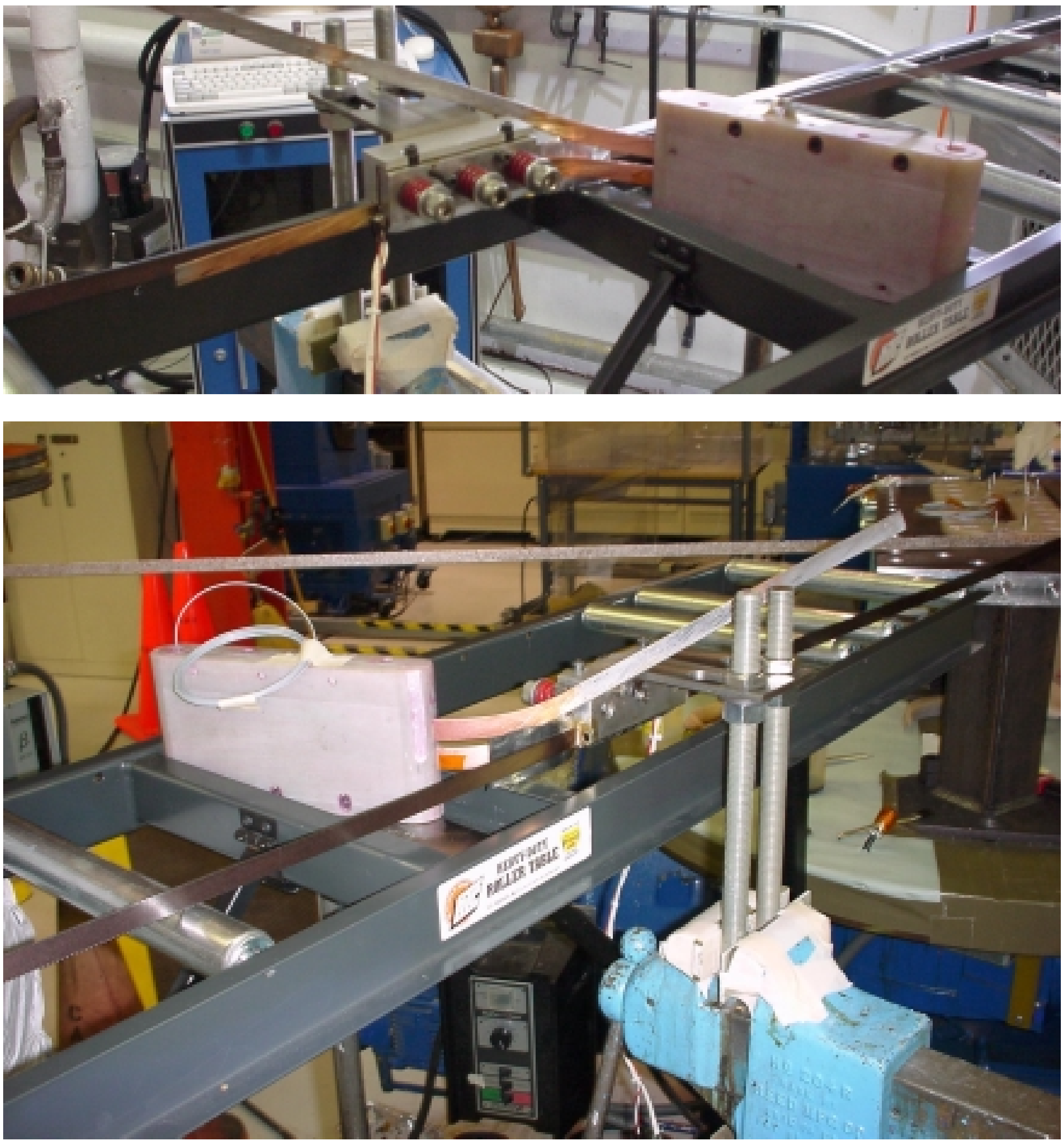


Figure 4: splice to NbTi cable used for coil to coil connection

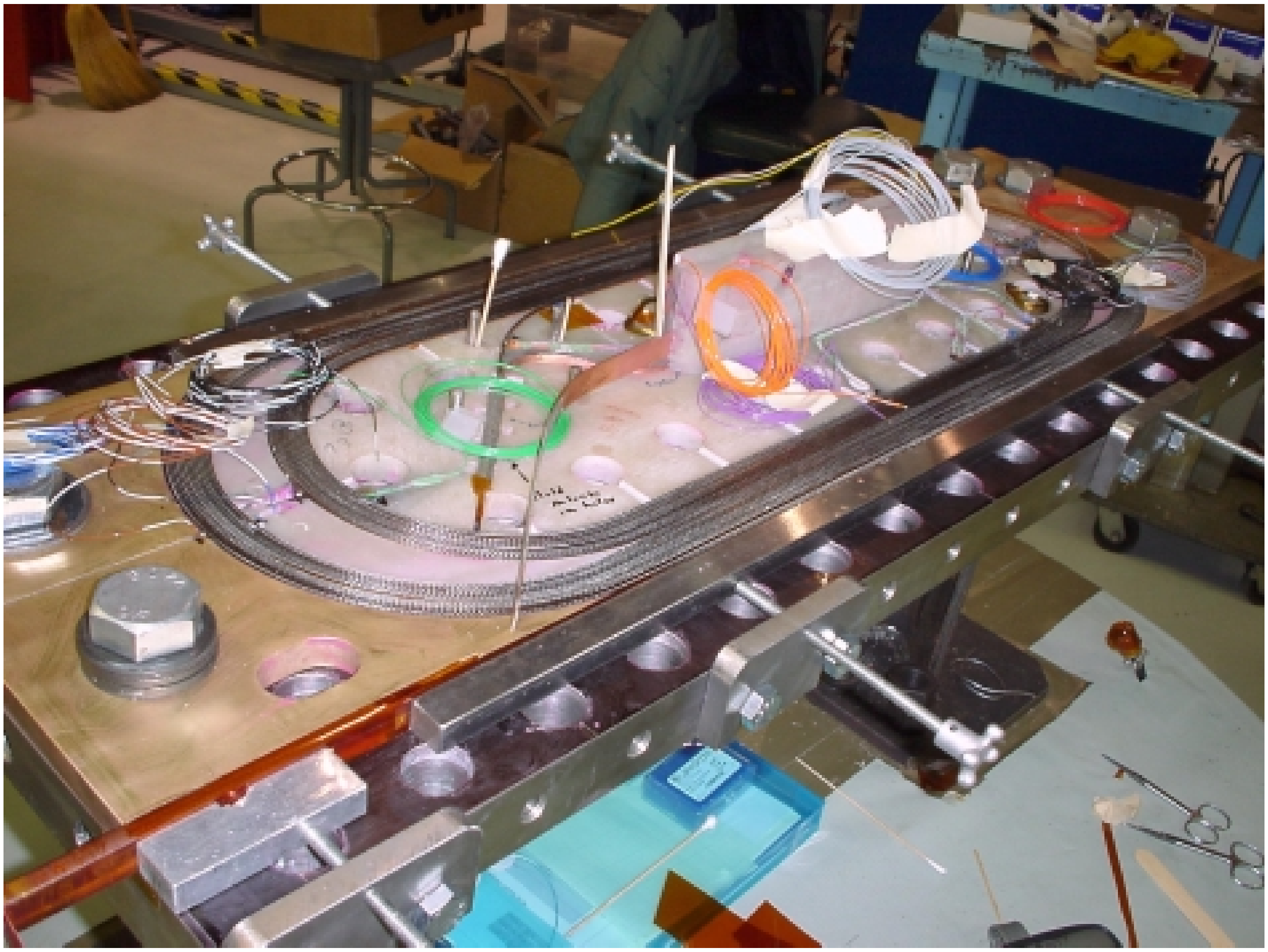


Figure 5: bottom coil during instrumentation

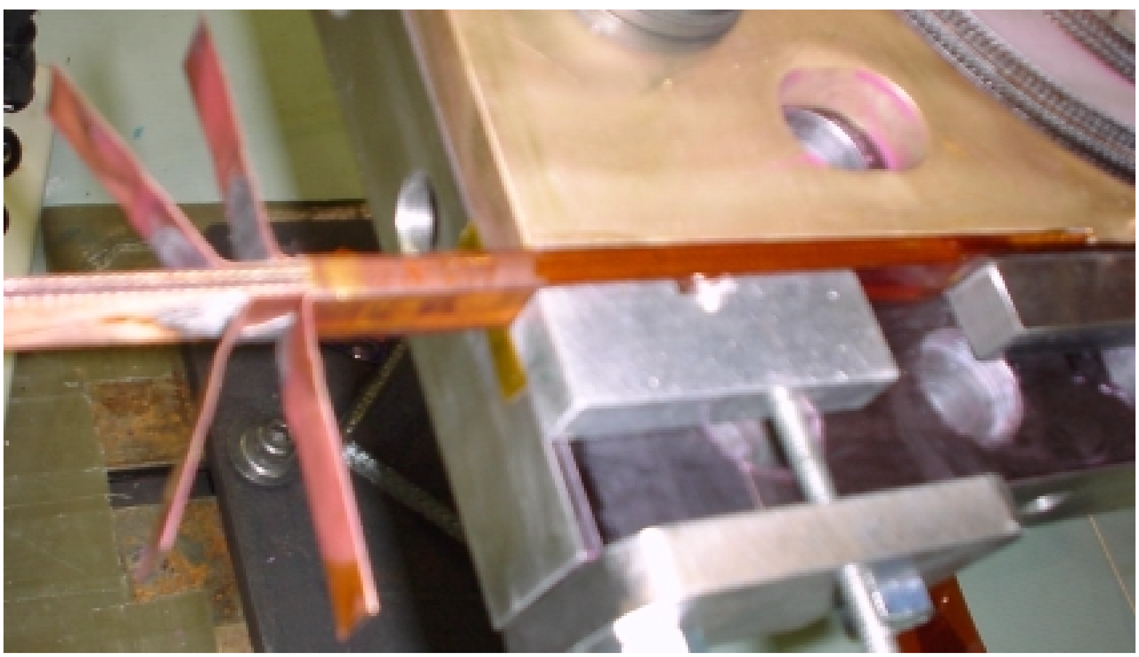


Figure 6: bottom coil – splice to NbTi leads

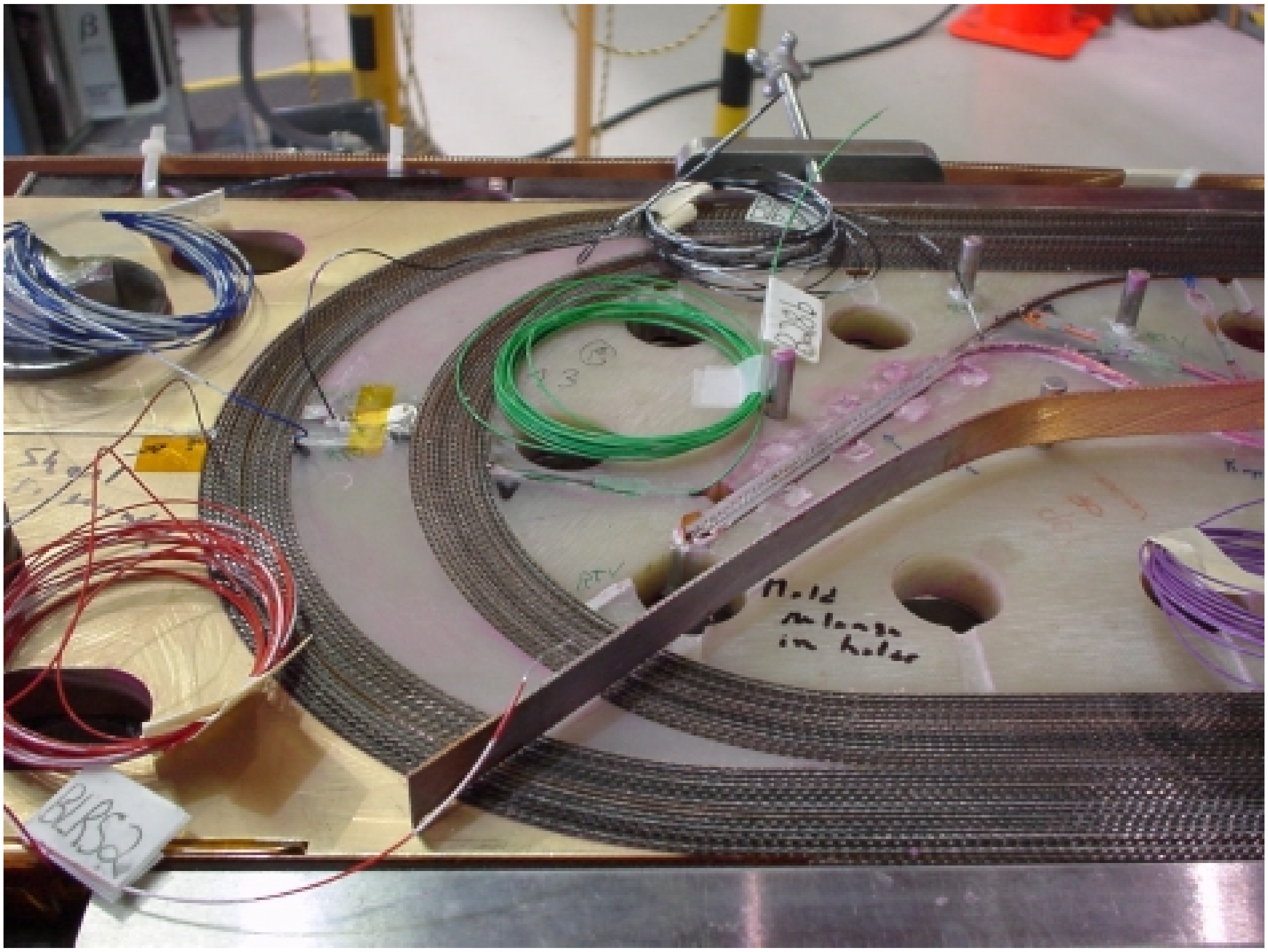


Figure 7: detail of bottom coil lead end

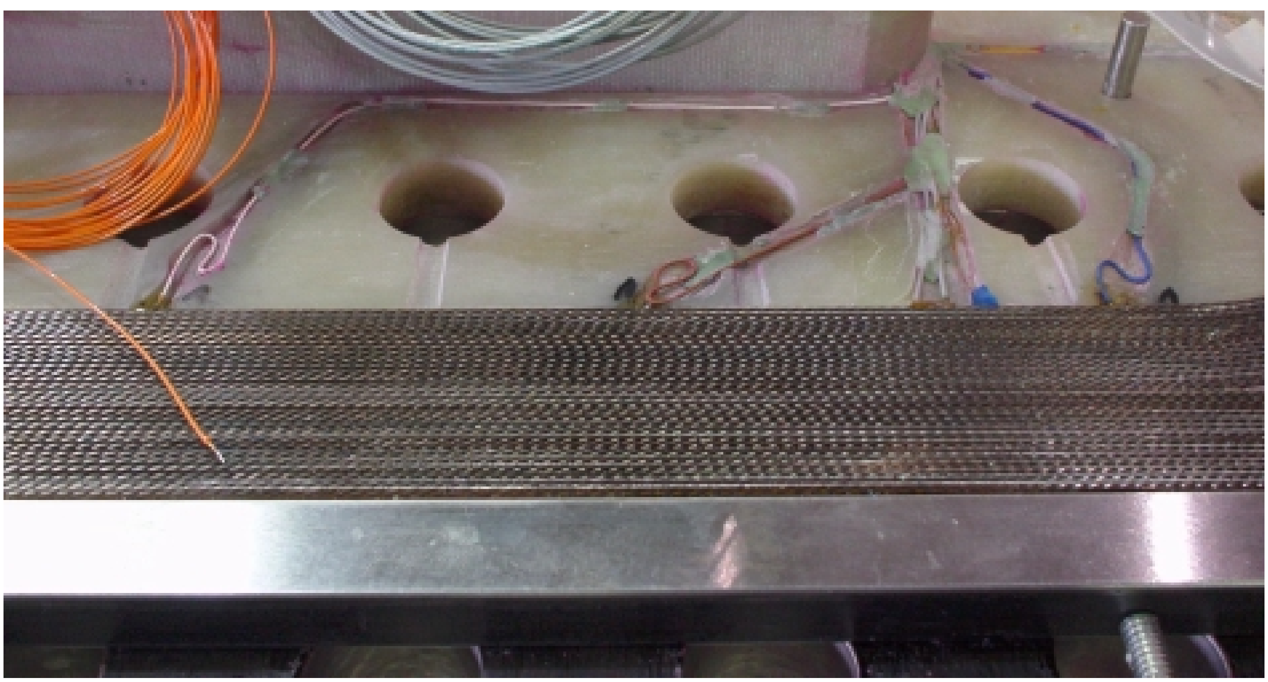


Figure 8: Voltage taps, spot heater (two wires) and temperature sensors (blue spot) on the innermost turn of the bottom coil

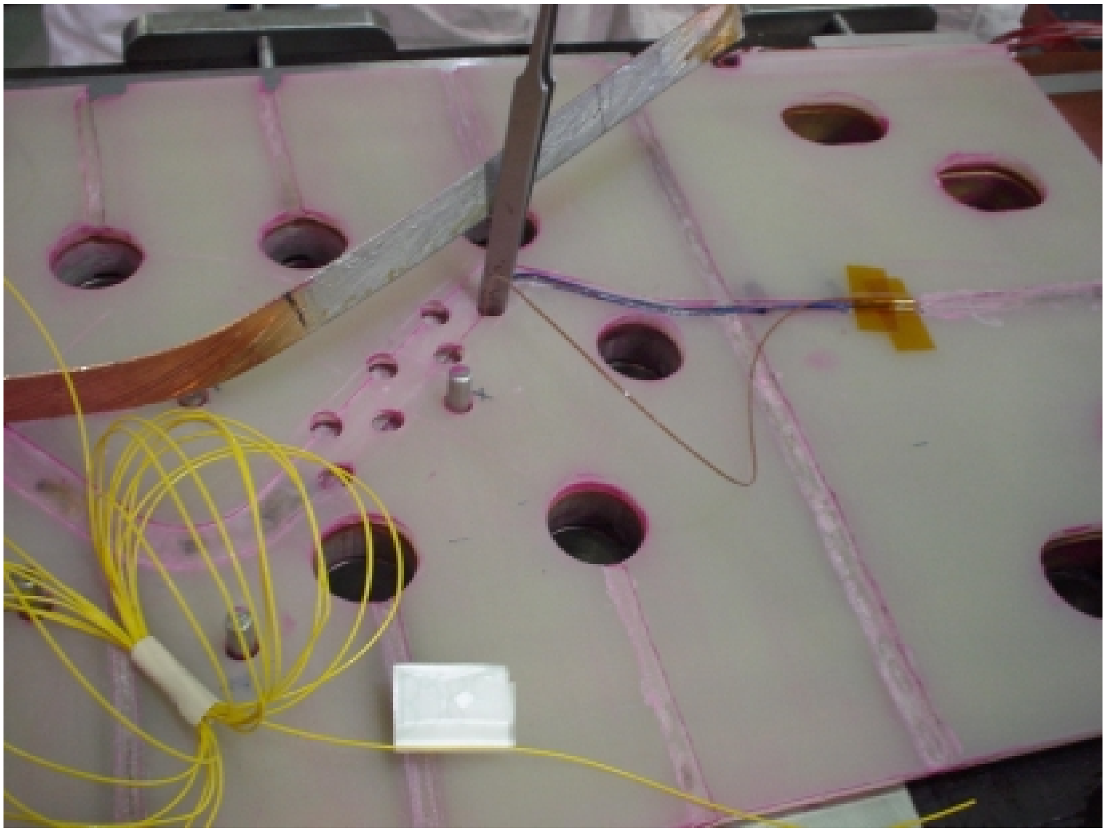


Figure 9: G10 plate installed on the top of the bottom coil

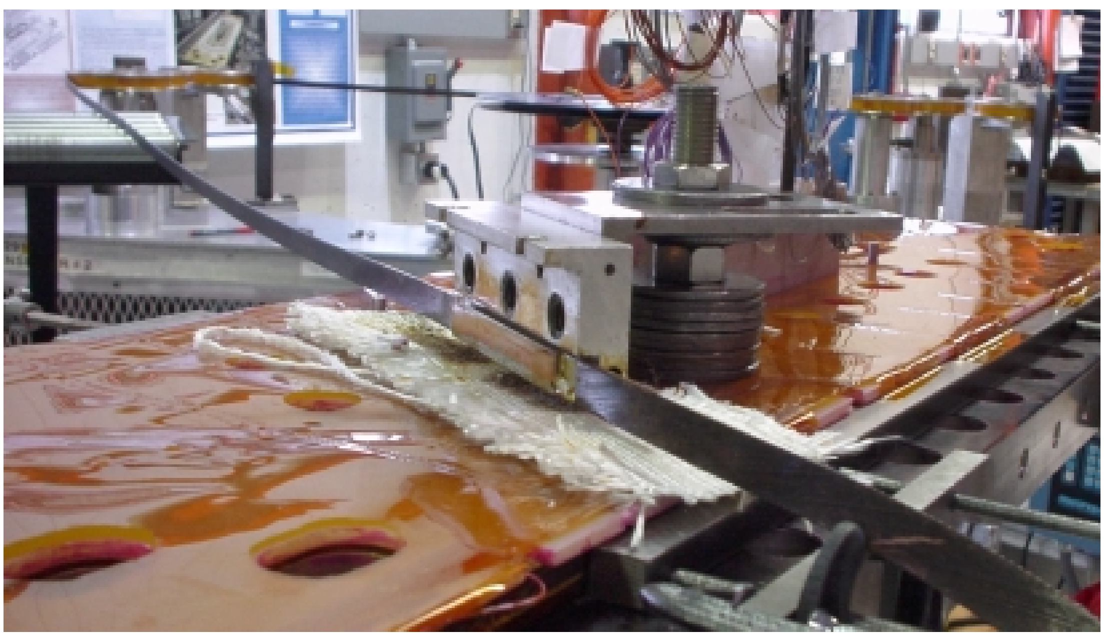


Figure 10: Inner splice of the top coil

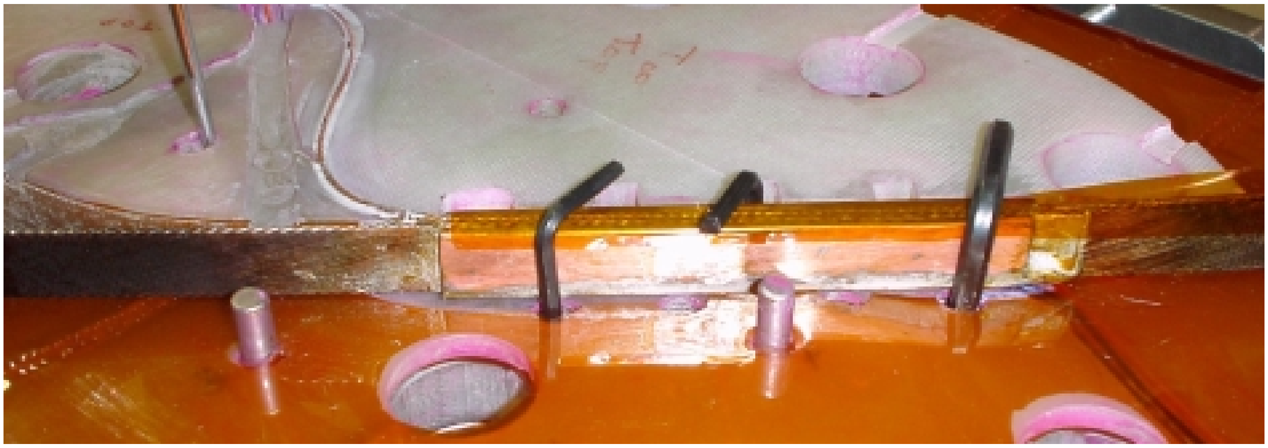


Figure 11: inner splice of the top coil is set in place

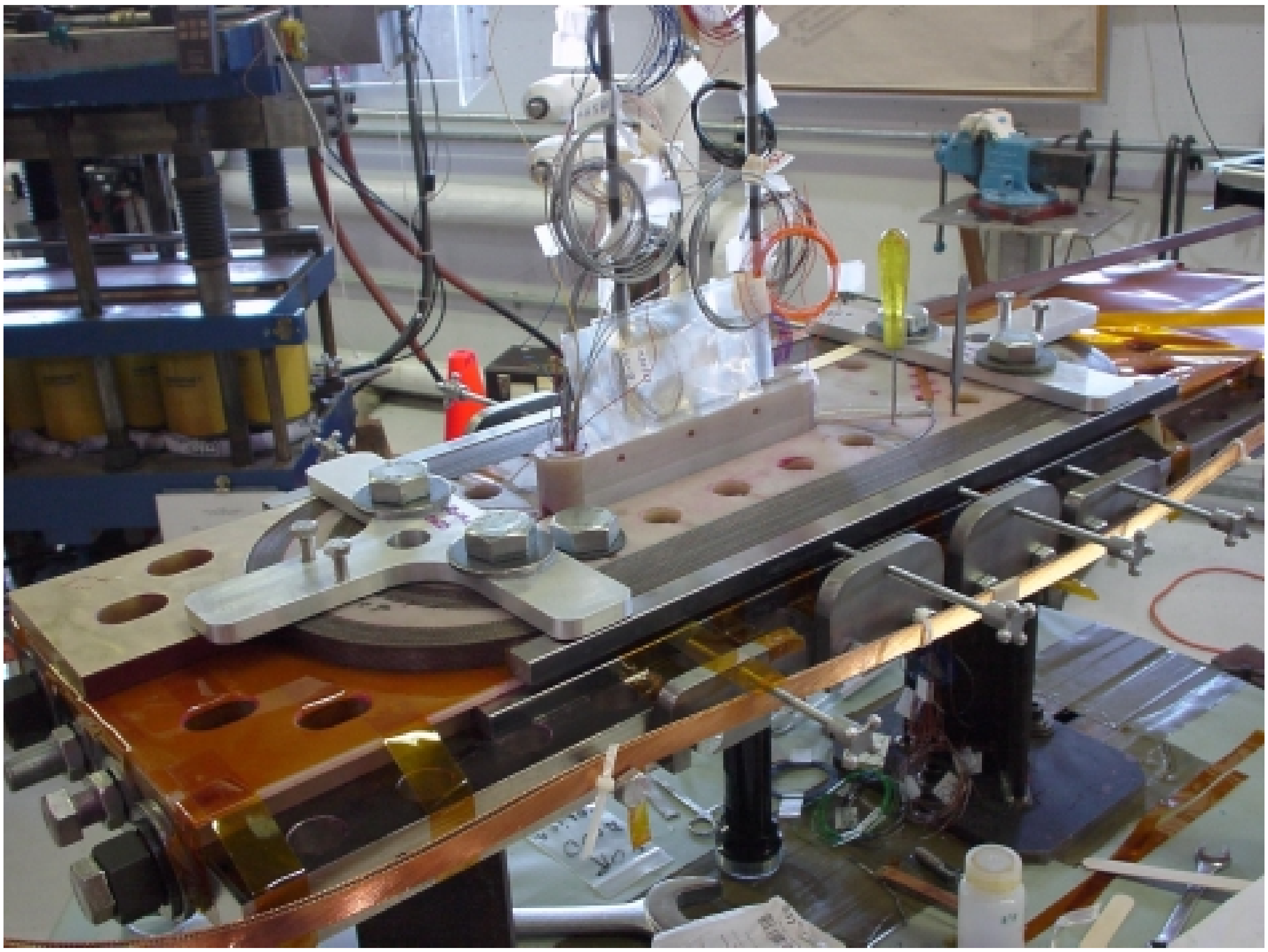


Figure 12: end of the winding of the top coil

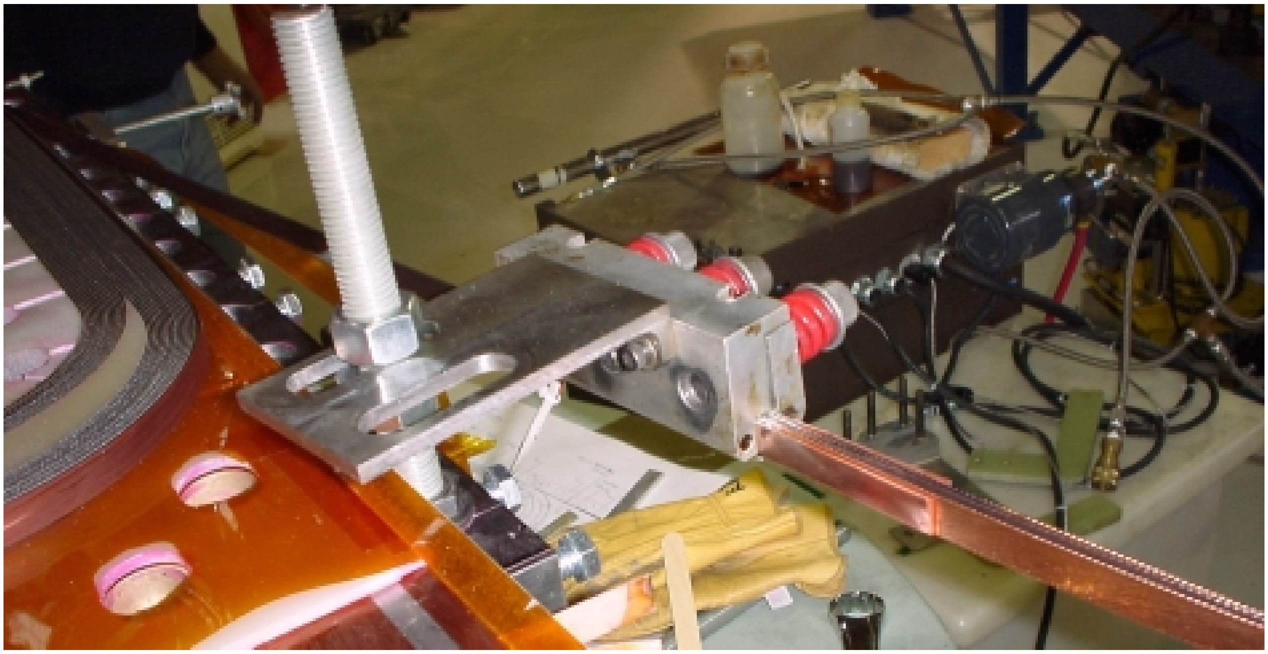


Figure 13: Splice to the NbTi current leads

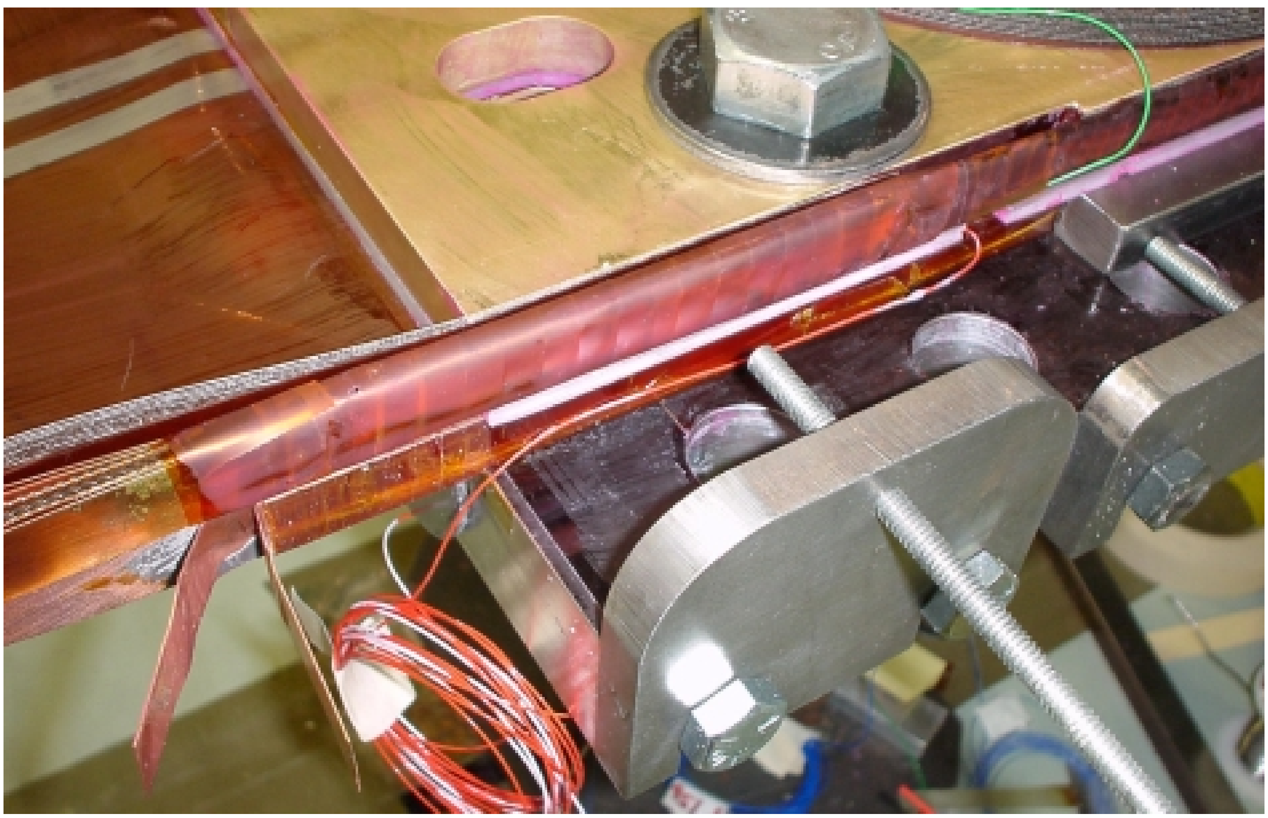


Figure 14: lead splice insulated and set in place

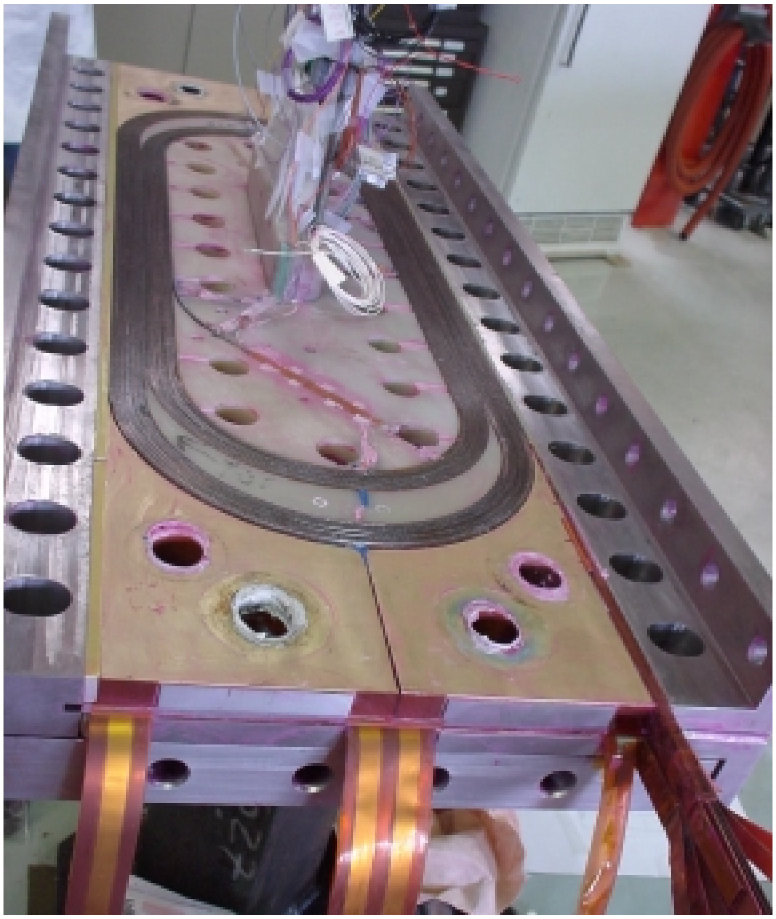


Figure 15: side pushers have been installed

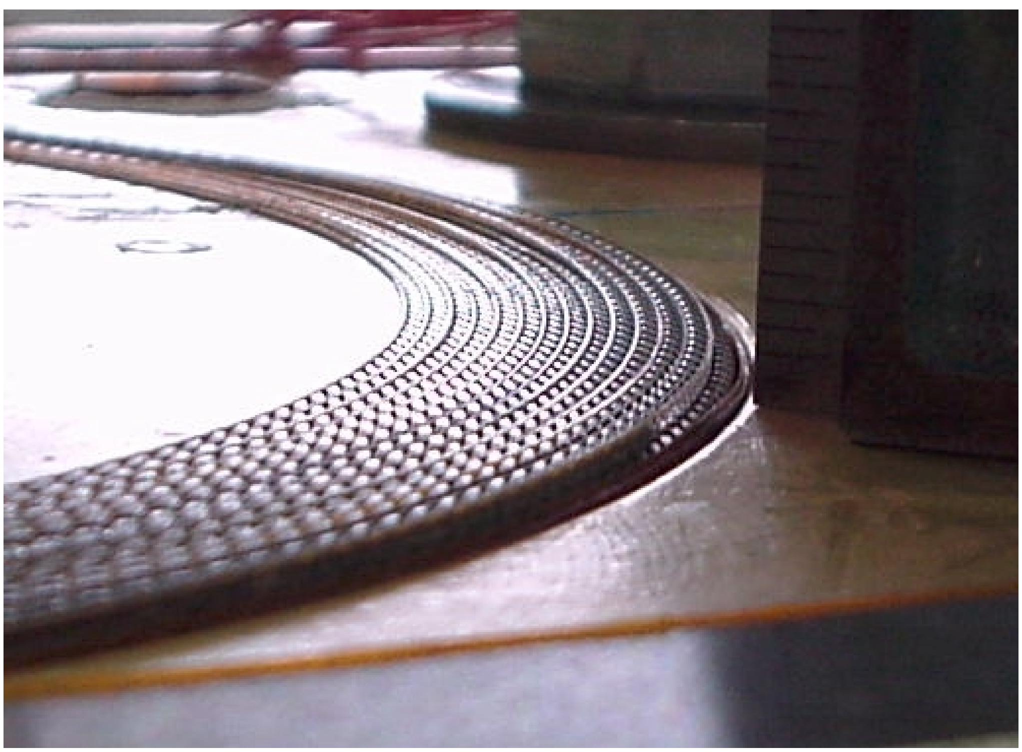


Figure 16: WE HAVE A PROBLEM: the cables in the outer block of the lead end moved upward

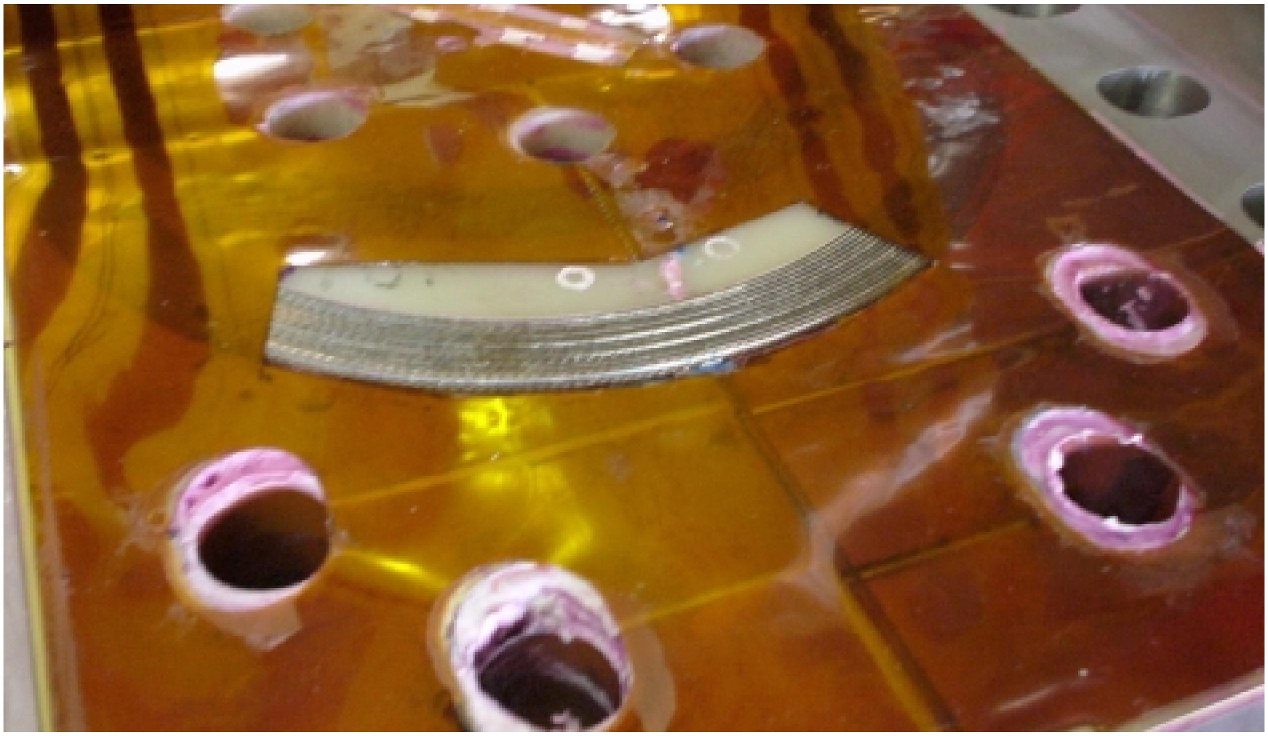


Figure 17: gap cut in the insulation behind the quench heater

Figure 18: quench heater on the top coil

Figure 19: preparation for impregnation; note the mold-release (pink), the RTV (red) and the grease (brown)

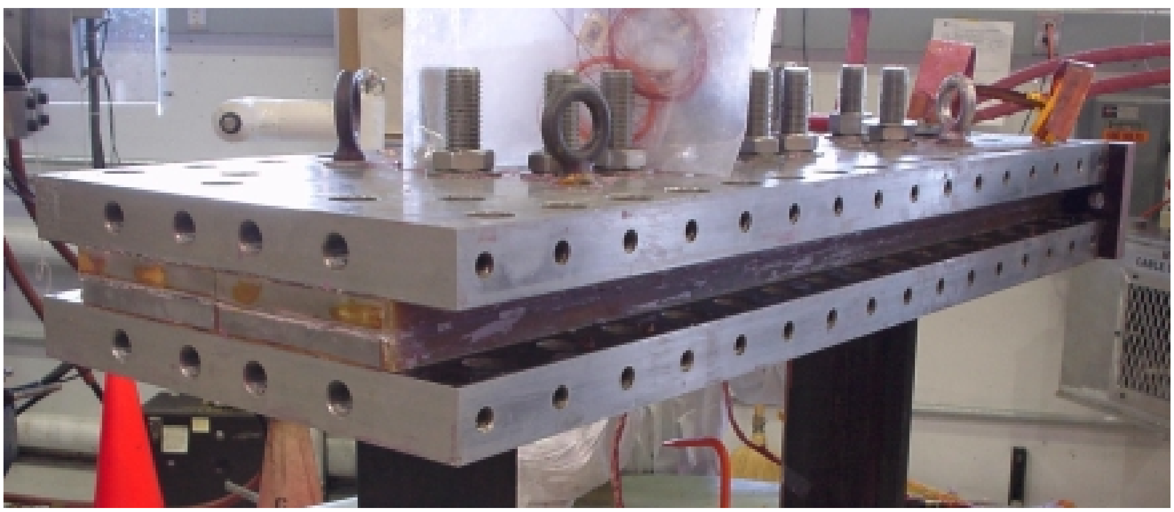


Figure 20: the racetrack is cleaned after impregnation; note that both side pushers and the return end plate have been removed

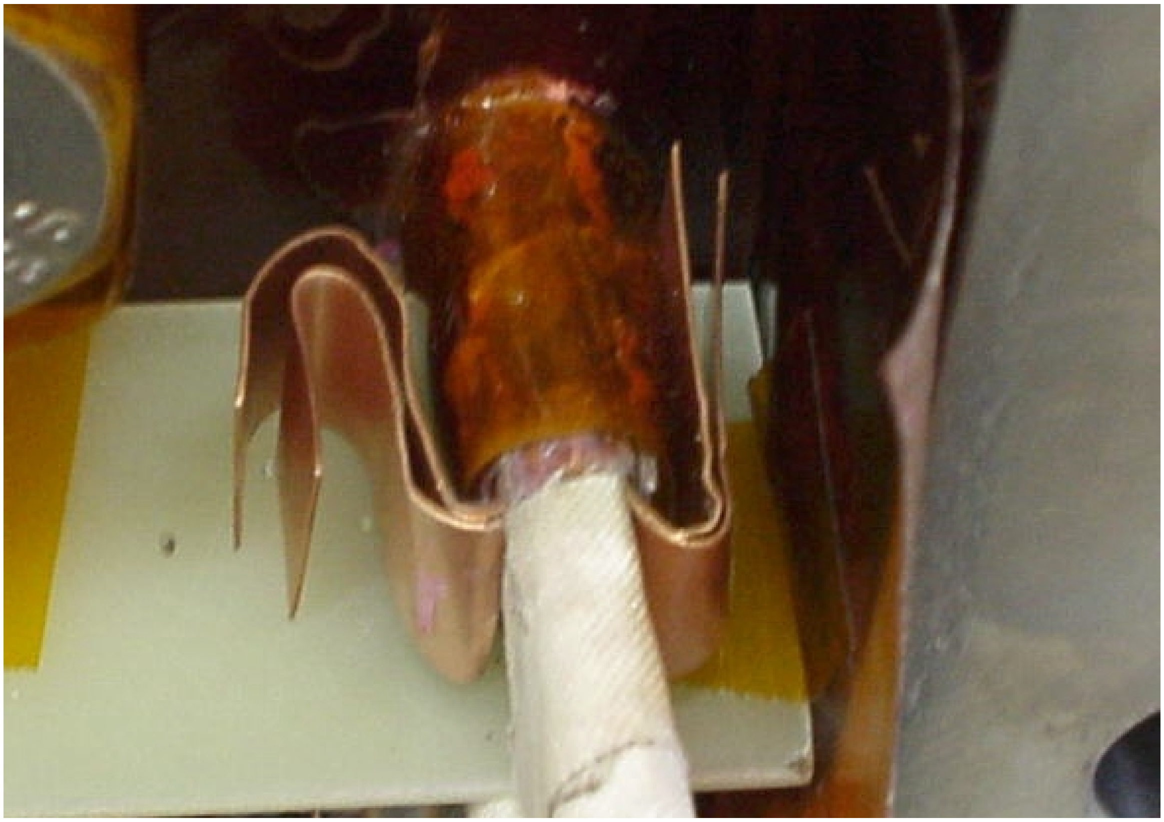


Figure 21: detail of the copper radiators used to cool the lead splice

Figure 22: ready for delivery to VMTF

Appendix 7

WORKS AFTER THE FIRST THERMAL CYCLE

Procedure to fix the racetrack

- open the lead end plate,
  - take pictures,
- machine the plate in order to have a larger hole for the leads,
- remove epoxy from the lead end
  - *old spacers were removed except the spacer on the bottom right coil*
- remove bottom end and increase thickness of spacers
  - take pictures
- analyze data from the bolts
- define new pre-stress application procedure:
  - end plates and side pushers should be loaded simultaneously in steps of 25% of the nominal total load
- apply pre-stress

Pre-stress was applied according to the following procedure:

- Pre-cycle: Hand-tighten all bolts on the side pushers and end plates until all the bolts are snug.
- All torques were applied to the bolts using two standard torque wrenches calibrated in in-lbs (for the bolts on side pushers and end plate) and ft-lbs (for main plates)
- Cycle 1: All 32 bolts on the side pusher were torqued to100 in-lbs starting with the outside bolts and moving towards the inside.
- Cycle 2: All 8 end bolts on the end plate were torqued to 150 in-lbs (outside bolts first to inside bolts next)
- Cycle 3: All 32side plate bolts were torqued to 200 in-lbs (outside bolts first to inside bolts next)
- Cycle 4: All 8 end bolts were torqued to 300 in-lbs (outside bolts first to inside bolts next)
- Cycle 5: All 32 side bolts were torqued to 300 in-lbs (outside bolts first to inside bolts next)
- Cycle 6: All 8 end bolts were torqued to 450 in-lbs (outside bolts to inside bolts)
- Cycle 7: All 8 end bolts were torqued to 600 in-lbs (outside bolts to inside bolts)
- Cycles 8 – 11: All main bolts were torqued to 1200 in-lbs in the following steps – 360 in-lbs, 720 in-lbs, 960 in-lbs and 1200 in-lbs.

Bolt stresses were monitored during the entire torquing cycle using calibrated strain gages mounted on four of the main bolts, two of the side bolts and two of the end bolts. The bolt load and coil pre-stresses are summarized in Table 3.

Bolts	Torque (in-lbs) per bolt	Average Load per bolt (lbs)	Total Load (lbs)	Stress per Coil (MPa)
Main	1200	4800	273600	2.42
Side	300	2200	70400	11.1
End	600	3300	26400	14.9

Table 3: Bolt loads and coil pre-stress summary for Thermal Cycle II

Instrumentation check before delivery:

- Hi-pot test (after pre-stress was applied):
  - Coil to ground: I<0.03 μA at 1000 V,
  - Coil to heaters: I<0.03 μA at 1000 V,
  - Heaters to ground: I<0.01 μA at 800 V,

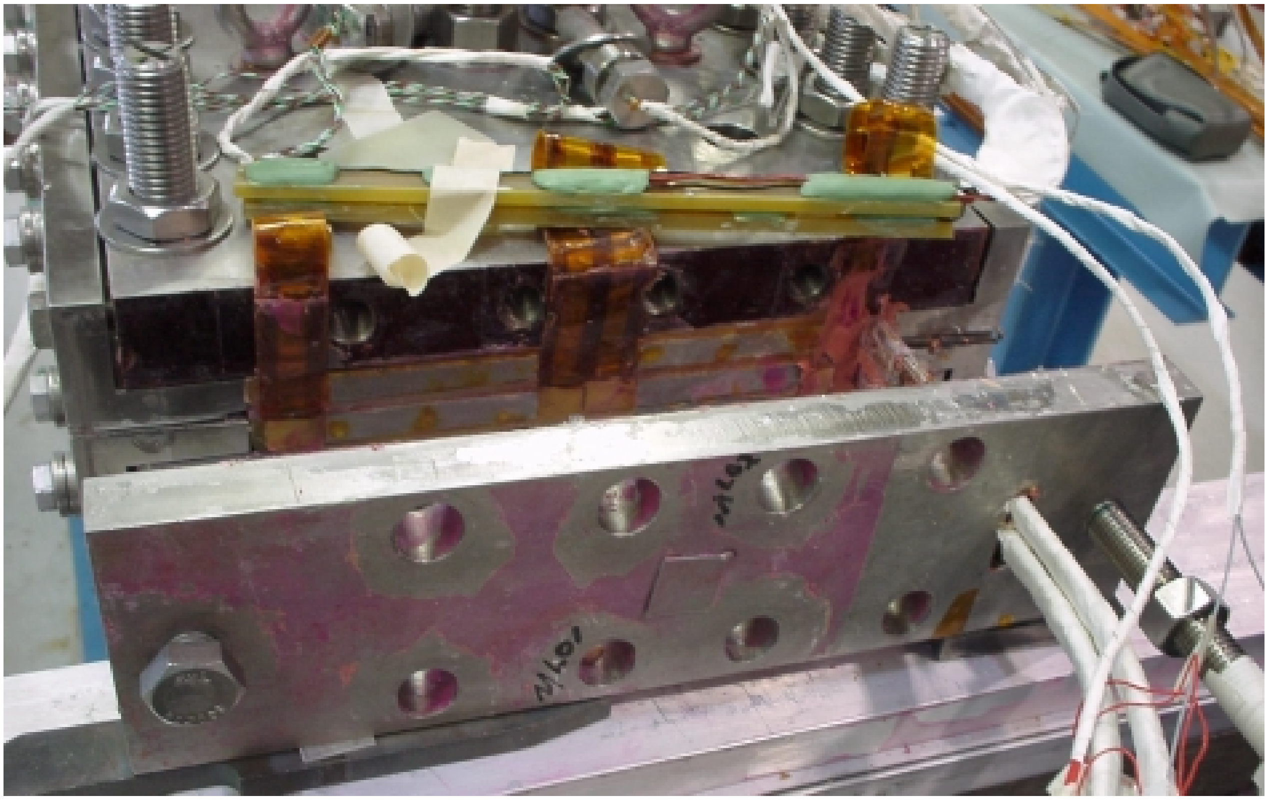


Figure 23: lead end plate removed after the first thermal cycle

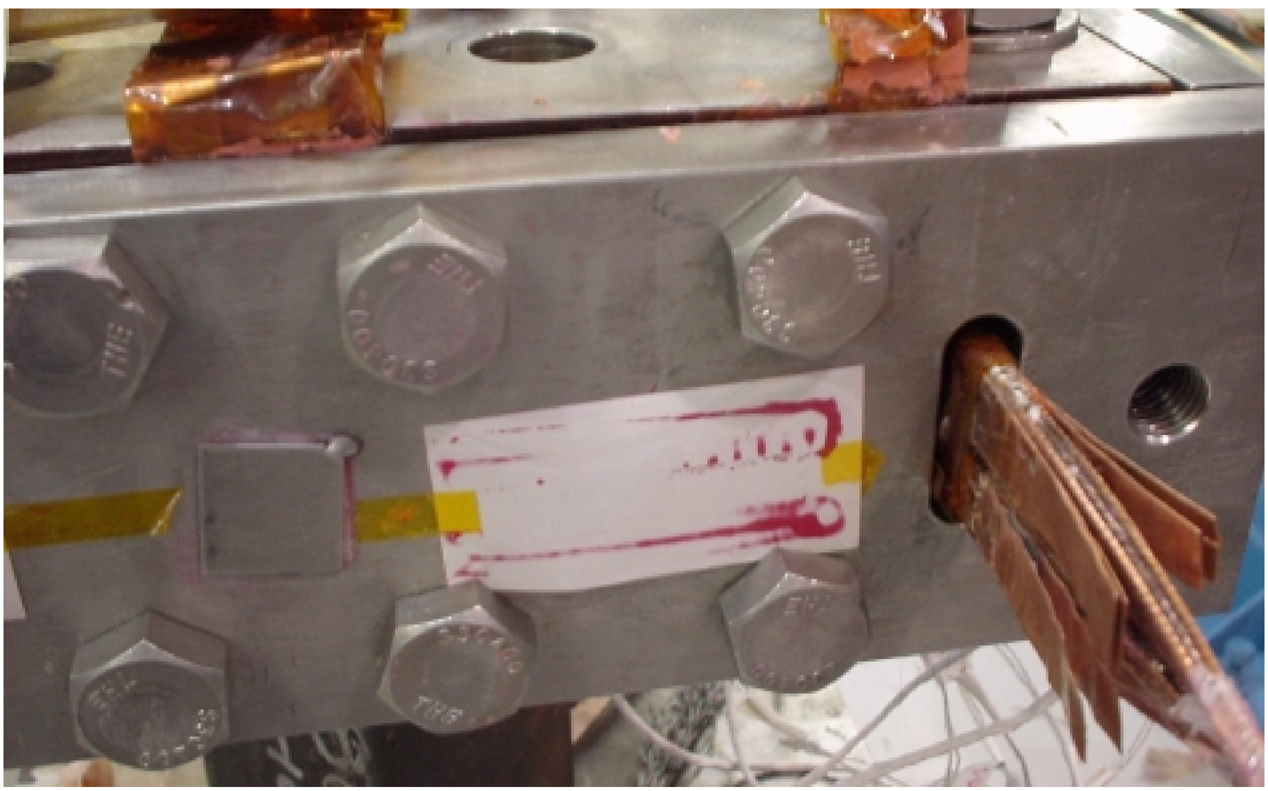


Figure 24: lead end plate back in position; sheets of Fuji film were used to check the pressure on the end shoes

Appendix 8

PARTIAL AUTOPSY AFTER THE 2ND THERMAL CYCLE

After the second thermal cycle the Racetrack was partially disassembled according to the following procedure:

- Instrumentation:
  - VT and SH: cut wires putting labels (to be used if we need to re-solder them),
  - Strain gauges: keep bolts attached to the connectors,
  - QH: keep them attached to the connector
- Bolts removal:
  - follow backward the procedure used to tighten the bolts
- Opening:
  - connect the G10 box to the bottom plate (free from the top plate)
  - keep down the central splice,
  - watch from sides and ends,
  - use the crane and/or the rods connecting the G10 box on the top.

The top plate came out easily. It wasn't bonded to the coil. The quench heater was very well bonded to the coil and we had to destroy it in order to remove it. The top coil was completely impregnated.
The surface of the quench heater wasn't smooth on the top of the area where the cables popped out and part of the insulation was removed. Therefore, before removing the quench heater we used Fuji paper in order to obtain a print of this area and check for stress-concentration spots.
Figure 25 shows the top coil after the quench heater has been removed.

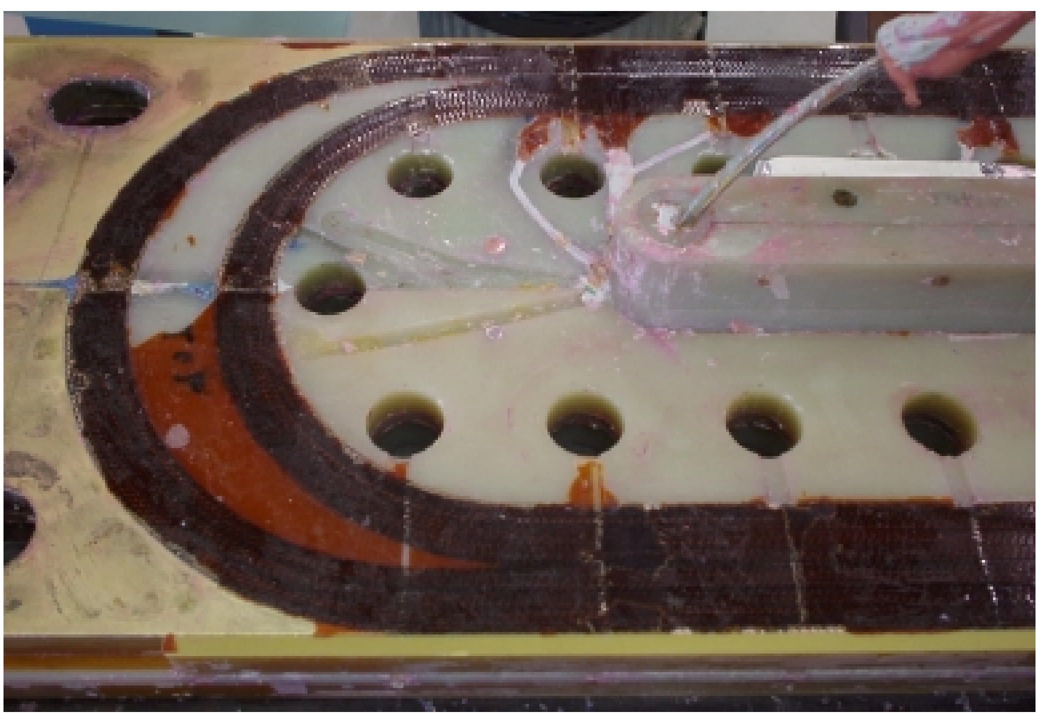


Figure 25: The top coil after the quench heater was removed

Appendix 9

INSPECTION OF CABLE LEFTOVERS

The analysis of quench performances showed the presence of a damage (or more) in the outermost turns of the top coil. The conductor in the outermost turns of the coils was in the innermost turns of the reaction spool. Damages occurred during the heat treatment should be seen on the leftovers of the cables. The leftovers were un-spooled and visually inspected. Series of regions with bumps were found (Fig. 26). Those bumps (four or five) have the same pattern in each region (about 5 inch long) and the distance from one region to the following is about 43-44 inches. They are less and less deep as they move from the beginning of the cable (starting from the beginning of the cable on the spool). We think that those bumps are the print of the copper shims placed in the transition between the first and the second turn. Those shims were set in that area in order to make the transition smooth. The distance from one region to the following is equal to the circumference of the spool. The leftover of the cable used for the bottom coil was quite long (more than 10 turns on the spool). Ten regions with prints could be seen. In the last one the print can hardly be felt by fingers and in the eleventh region it may be considered negligible.
The leftover of the cable used for the top coil was much shorter (about six turns of the reaction spool). Six regions with bumps could be seen and it is very likely that some regions with bumps were in the cable used for this coil. Some bumps should have been in the Nb_3Sn lead (about 2 m long) but a few may have been in the winding.

Figure 26: section of cable leftover with bumps